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Shear behaviour of rock joints with unsaturated infill

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Abstract

Behaviour of soil-infilled rock joints has significant importance with respect to the strength of fractured rock mass. The presence of even a small amount of fine-grained infill material within a joint can reduce its shear strength considerably, depending on the degree of saturation of infill. Therefore, it is crucial to examine how the infill material can adversely affect the joint shear strength. Previous studies of infilled joints have mainly been focused on idealised regular joint patterns owing to the simplicity and reproducibility in laboratory testing. Current literature on infilled rock joints has also neglected the effect of the degree of saturation of infill on the shear behaviour. In most instances, fully saturated infill has been used or assumed, and the contribution of matric suction on the shear strength of joints having unsaturated infill has not been studied. In this study, a series of triaxial tests on natural joint profiles having joint roughness coefficient (JRC) of 10-12 is carried out at constant moisture content. A semi-empirical model is proposed and validated on the basis of laboratory data.

Keywords

behaviour, joints, shear, infill, rock, unsaturated

Disciplines

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TECHNICAL NOTE

Shear behaviour of rock joints with unsaturated infill

B. INDRARATNA*, W. PREMADASA† and E. T. BROWN‡

Behaviour of soil-infilled rock joints has significant importance with respect to the strength of fractured rock mass. The presence of even a small amount of fine-grained infill material within a joint can reduce its shear strength considerably, depending on the degree of saturation of infill. Therefore, it is crucial to examine how the infill material can adversely affect the joint shear strength. Previous studies of infilled joints have mainly been focused on idealised regular joint patterns owing to the simplicity and reproducibility in laboratory testing. Current literature on infilled rock joints has also neglected the effect of the degree of saturation of infill on the shear behaviour. In most instances, fully saturated infill has been used or assumed, and the contribution of matric suction on the shear strength of joints having unsaturated infill has not been studied. In this study, a series of triaxial tests on natural joint profiles having joint roughness coefficient (JRC) of 10–12 is carried out at constant moisture content. A semi-empirical model is proposed and validated on the basis of laboratory data.

KEYWORDS: partial saturation; rocks/rock mechanics; shear strength

INTRODUCTION

The shear behaviour of infilled rock joints is controlled by several parameters, including the infill thickness, joint roughness, drainage condition and degree of infill saturation (Barton, 1974; Ladanyi & Archambault, 1977; Indraratna *et al.*, 2012). Even though the influence of a number of parameters such as the joint roughness and infill thickness has been studied in the past, the degree of infill saturation has received limited attention. Although Barton (1974) explained the importance of the in situ water content of infill on the overall shear strength of rock joints, subsequent studies have either considered a fully saturated infill or have conveniently ignored the role of unsaturation (Ladanyi & Archambault, 1977; Lama, 1978; Pereira, 1990; Indraratna *et al.*, 2005, 2008, 2010). For adverse climatic conditions, such as in prolonged periods of heavy rainfall, most joints act as conduits (Barton, 1974), making the infill wet or even saturated. During dry seasons, the degree of infill saturation may decrease, increasing the overall shear strength of the joint.

This technical note reports the initial stages of a novel study involving the triaxial testing of infilled model joints under different initial degrees of saturation. A series of constant water content tests was conducted on soil-infilled natural joint profiles imprinted on gypsum plaster. An extension of a previously proposed semi-empirical mathematical model has been developed for the unsaturated condition and validated.

The significance of the preliminary work reported here is that, for the first time, an experimentally validated conceptual model for the shear strengths of unsaturated soil-infilled rock joints is presented. It is common practice in jointed rock engineering to base designs on the lowest joint shear strength, that is, the value under fully saturated infill conditions. However, given that a considerable portion of the jointed rock mass in a slope, for example, may be located above the groundwater table, and that full saturation of the infill may not necessarily occur, even after heavy or prolonged precipitation, introducing the role of unsaturated infill using the model developed here could make future analyses and designs more realistic, and potentially reduce the costs of some slope stabilisation schemes.

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MODEL DEVELOPMENT

The semi-empirical infilled joint model proposed earlier by Indraratna *et al.* (2005) has been extended in this study to incorporate the effect of infill saturation. The shear strength (τ) of an infilled joint can be expressed using two algebraic functions (Indraratna *et al.*, 2005)

$$\tau = A + B \tag{1}$$

where function A is the contribution from the joint surfaces and function B is the contribution from infill. Function A has a maximum when there is no infill in the joint, and a minimum value of zero when the contact between the two rock walls is prevented by a critical infill thickness. Function B increases from zero (no infill) to its optimum value (i.e. shear strength of infill alone). Fig. 1 illustrates the conceptual development of the shear strength model for partially saturated infilled joints. Here, the function A has been modified with the Barton & Choubey (1977) equation to include the joint roughness coefficient (JRC) and joint compressive strength (JCS). Function B is inspired by Vanapalli *et al.* (1996) to include the matric suction of unsaturated infill, thus

$$A = [\sigma_n \times \tan(\phi_b + \mathrm{JRC} \times \log(\mathrm{JCS}/\sigma_n))] \times (1 - k_s)^{\alpha} \tag{2}$$

and

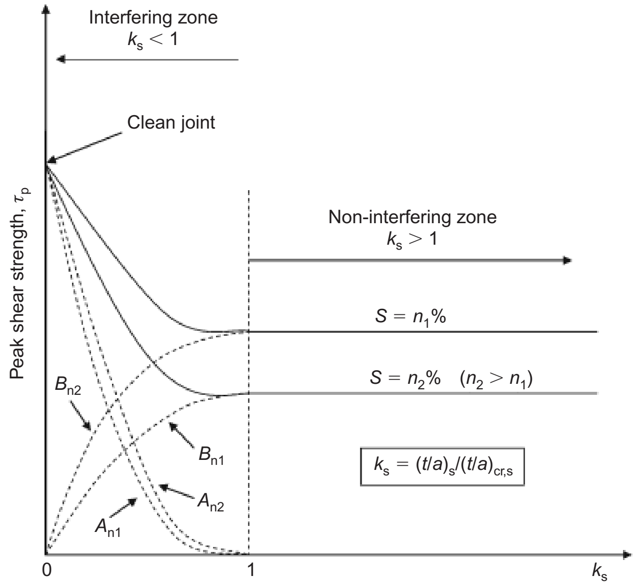

Fig. 1. Extended peak shear strength model including the effect of infill saturation

$$B = c_t + [(\sigma_n - u_a)\tan\phi'] \times \left(\frac{2}{1 + 1/k_s}\right)^{\beta} \tag{3}$$

where

$$k_s = (t/a)_s/(t/a)_{cr,s} \tag{4a}$$

$$c_t = c' + (u_a - u_w)\left[(\tan\phi')\left(\frac{S_r - S_{res}}{100 - S_{res}}\right)\right] \tag{4b}$$

In the parameter k_s (i.e. normalised infill thickness ratio), $(t/a)_s$ is the mean infill thickness (t) to asperity height (a) ratio of an infilled joint at a given degree of saturation, and the subscript 'cr' represents its critical value. In equations (2)–(4), ϕ_b is the basic friction angle of the joint surfaces, σ_n is the normal stress, c' and ϕ' are the effective cohesion and angle of shearing resistance of saturated infill, respectively, $(u_a - u_w)$ is the matric suction of infill, S_r is the degree of infill saturation, S_{res} is the residual degree of saturation, and α and β are empirical constants.

Two major shear strength zones can be identified with respect to the normalised infill thickness ratio (k_s).

For the rock–infill interference zone ($k_s < 1$)

$$\tau = \{\sigma_n \times \tan[\phi_b + \text{JRC} \times \log(\text{JCS}/\sigma_n)]\} \times (1 - k_s)^{\alpha} + c_t + [(\sigma_n - u_a)\tan\phi'] \times \left(\frac{2}{1 + 1/k_s}\right)^{\beta} \tag{5}$$

For the non-interference zone ($k_s > 1$), where the shear strength is governed only by the infill

$$\tau = c_t + [(\sigma_n - u_a)\tan\phi'] \tag{6}$$

EXPERIMENTAL PROCEDURE

Specimen preparation

Joint profiles having JRC in the range of 10–12 were obtained from a rock slide at Kangaroo Valley, and replicated on gypsum plaster surfaces using silicone rubber. Jointed cylindrical specimens of 54 mm in diameter with a dip angle of 60° (Fig. 2(a)) were cast in gypsum plaster (plaster/water ratio = 7:2 by weight). The roughness amplitude or asperity height of the natural joint was determined according to ISRM (1981) recommendations. A mean asperity amplitude (a) and a mean infill thickness (t) were measured at several points on the joint surface (Figs 2(b) and 2(c)). The appropriate infill thickness to asperity height ratio (t/a) could then be determined using the mean values of a and t.

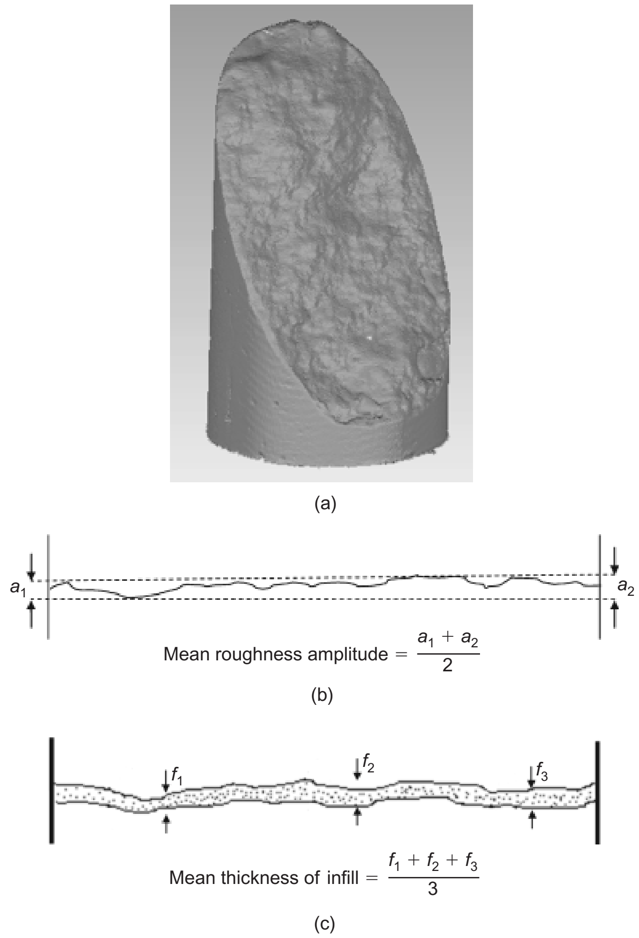

Fig. 2. (a) Surface profile used for laboratory testing; (b) calculation of mean roughness amplitude (ISRM, 1981); (c) calculation of mean thickness of infill (ISRM, 1981)

Indraratna (1990) proposed the use of hydrated gypsum cement to model soft sedimentary rock joints. The plaster specimens typically have an unconfined compressive strength (σ_c) of 60–70 MPa after 2 weeks of curing at a controlled temperature of 40°C. An organic waterproofing sealant was applied over the cured joint surfaces to ensure no moisture loss from the infill to plaster during testing. The infill material can be described as silty clay (25% fine sand and 75% kaolinite) with a liquid limit of 39% and a plastic limit of 20%. The shear strength parameters of the saturated infill ($c' = 13{\cdot}4$ kPa, $\phi' = 21°$) was determined using a drained direct shear apparatus. The infill was mixed to a predesired moisture content and spread over the waterproof joint profile using a spatula, and statically compacted.

Testing procedure

The cylindrical jointed specimens were tested using a high-pressure (two-phase) triaxial apparatus (Indraratna & Haque, 1999). Provided that the drainage valves remain shut during testing, a condition of constant moisture can be established. The test specimen was wrapped in a neoprene membrane and sheared at a strain rate of 0·01 mm/min to be consistent with the strain rates used in a number of previous studies (Thu *et al.*, 2006; Fredlund *et al.*, 2012). More than 60 constant moisture content triaxial tests were carried out on replicated natural joints for confining pressures of 300, 500 and 900 kPa, and at initial degree of saturation of 35%, 50%, 60%, 70%, 85% for *t/a* ratios of 0, 0·26, 0·51, 1·53 and 2·05 respectively. Fully saturated infilled joints could not be tested owing to the difficulty posed in preparing specimens, as the infill became slurry-like when approaching saturation. At the end of each test, the moisture content of the infill was measured and compared with the initial value, and the insignificant difference between the two measurements ($< 0{\cdot}1$) confirmed the constant moisture condition.

To adequately describe the hydraulic properties of a material under unsaturated conditions, it is necessary to establish a relationship between suction and the amount of water present, that is the soil-water characteristic curve (SWCC). For this infill, SWCC was determined using the test data obtained from the pressure plate apparatus and chilled mirror hygrometer (ASTM, 2008) as shown in Fig. 3. The data were interpolated using the well-known Van Genuchten (1980) relationship adopting the least-squares method. The interpolated best-fit parameters are shown in Fig. 3 along with the experimental data.

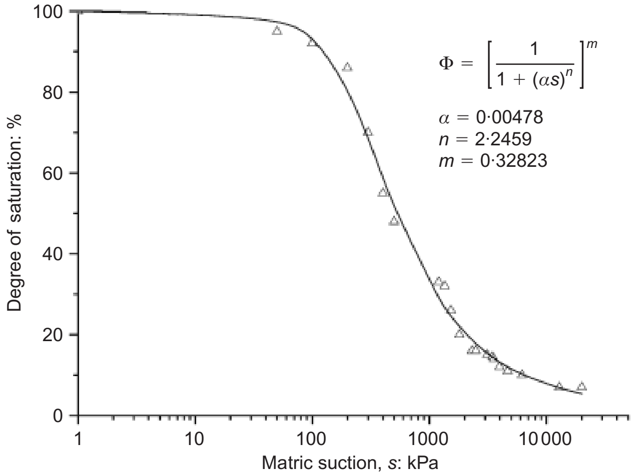

Fig. 3. Soil-water characteristic curve for the infill

RESULTS AND DISCUSSION

Deviator stress and dilation data obtained by triaxial testing for the range of *t/a* ratios tested at 50% and 70% infill saturation under a confining pressure of 500 kPa are presented in Fig. 4. When the infill is comparatively thin (i.e. $t/a = 0{\cdot}26$ and 0·51), the stress–strain plot exhibits two peaks (Indraratna *et al.*, 2008). The first peak corresponds to the yielding of the soil infill and, beyond this point, asperity interference prevails, causing a significant increase in dilation. The second peak is largely influenced by rock–rock contact (albeit some infill is still present). This double-peak phenomenon becomes less pronounced as the infill thickness increases. In a natural joint the roughness is spatially distributed over the joint profile, unlike idealised regular joints. Therefore, when the steepest asperity is sheared off, the contact will then transfer to the next steepest asperity. This process continues until both sliding and shearing of asperities occur simultaneously. Hence, in a natural joint a distinct second peak may not be observed

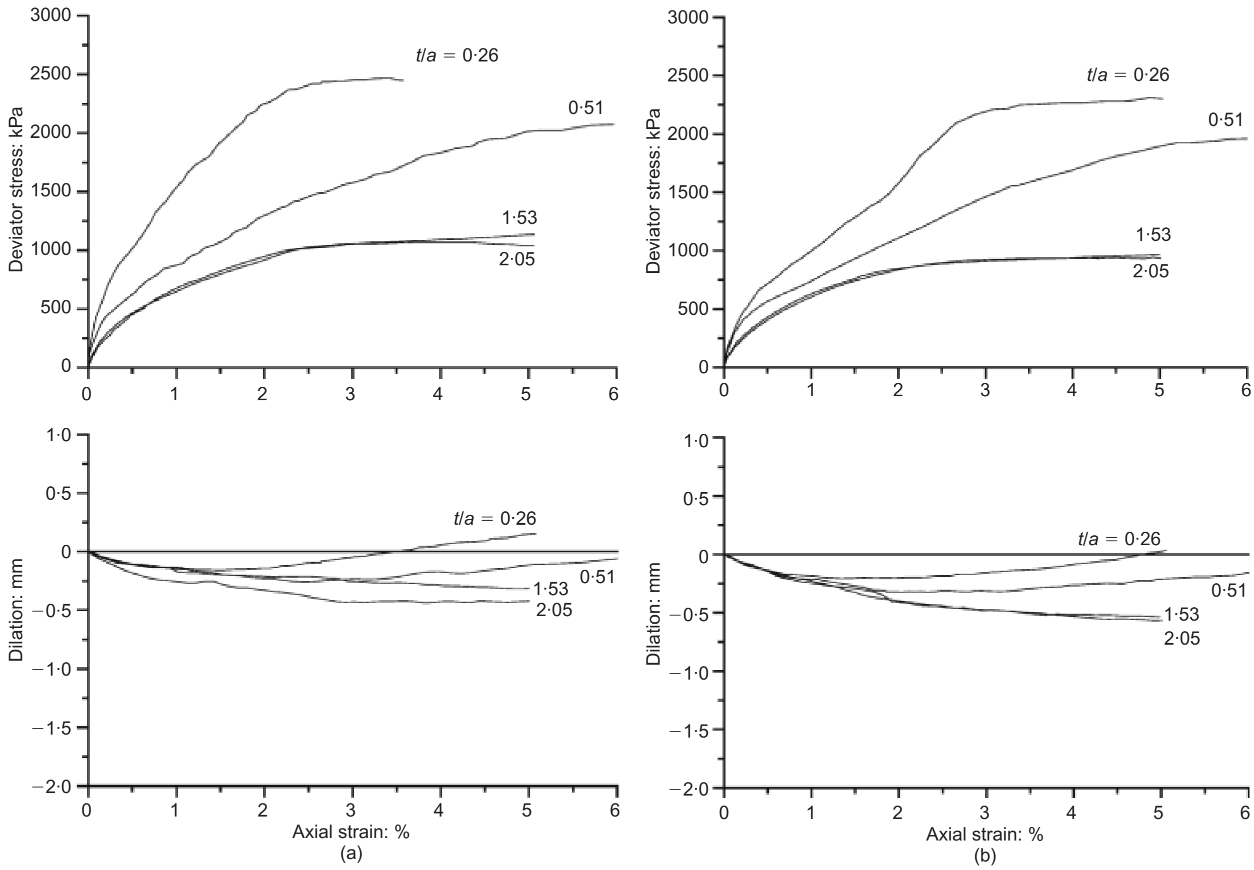

Fig. 4. Shear behaviour of replicated natural joints for infill saturations of (a) 50% and (b) 70%, under 500 kPa confining pressure

(Fig. 4), unlike in idealised saw-tooth joints. When the *t/a* ratios are 1·53 and 2·05, the joint only shows a similar pattern of shearing through infill alone. After a certain critical infill thickness to asperity height ratio $(t/a)_{cr}$ is attained, the asperity interference diminishes and shearing occurs solely through the infill accompanied by joint compression.

For the smaller *t/a* ratios of 0·26 and 0·51, the initial compression is followed by dilation (Fig. 4). This predominantly dilative behaviour is attributed to asperity interference (i.e. overriding) when the infill thickness is relatively thin. As expected, when the degree of saturation of infill is increased from 50% to 70%, the deviator stress decreases (Fig. 4). In addition, the observed volumetric behaviour is mainly compressive when the degree of infill saturation is relatively high. In contrast, specimens with a lower degree of saturation exhibit predominantly dilative behaviour. Thu *et al.* (2006) have also observed a similar behaviour for a processed kaolin clay.

The silty clay seam inside the tested rock joints varied from 1 to 8 mm in thickness (corresponding to *t/a* ratios of 0·26 to 2·05). Since this was a relatively thin seam, it was not feasible to install a small suction probe inside the joint to measure the negative pore pressures, owing to the risk of damage or debonding during shearing. Moreover, during the shearing process, the broken asperities (gouge) contaminate the infill. In this case, the final value of suction computed using methods such as the filter paper technique is not realistic. Therefore, in this study, the shear behaviour of the infilled joints was modelled only considering the initial suction of the infill at the start of test.

The purpose of any shear strength model in rock joints is to provide better assessment of stability or factor of safety (e.g. unstable slope or wedge). With a field perspective, the use of the degree of infill saturation at failure may not be a feasible option. However, at least knowing the initial degree of saturation and the corresponding matrix suction is a more viable and practical alternative. As no current standards are available for testing of unsaturated infilled joints, it is anticipated that this study will provide a preliminary platform to assess the shear strength of infilled joints and future applications to rock mass behaviour.

Model validation

As observed from the laboratory data, the peak shear stress decreases when the *t/a* ratio is increased to its critical value, $(t/a)_{cr}$, and remains constant thereafter. However, the value of $(t/a)_{cr}$ was observed to vary with the initial degree of infill saturation. Therefore, the normalised infill thickness ratio (k_s) introduced in equation (4a) better represents the interference and non-interference zones. Fig. 5 shows the model predictions based on equations (5) and (6) for JRC = 11 and infill saturation of 50% and 70%. An acceptable match between the model predictions and laboratory data was found, for which the associated empirical parameters could be determined by multiple regression analysis. The empirical parameters along with the critical *t/a* ratios for each degree of infill saturation are summarised in Table 1.

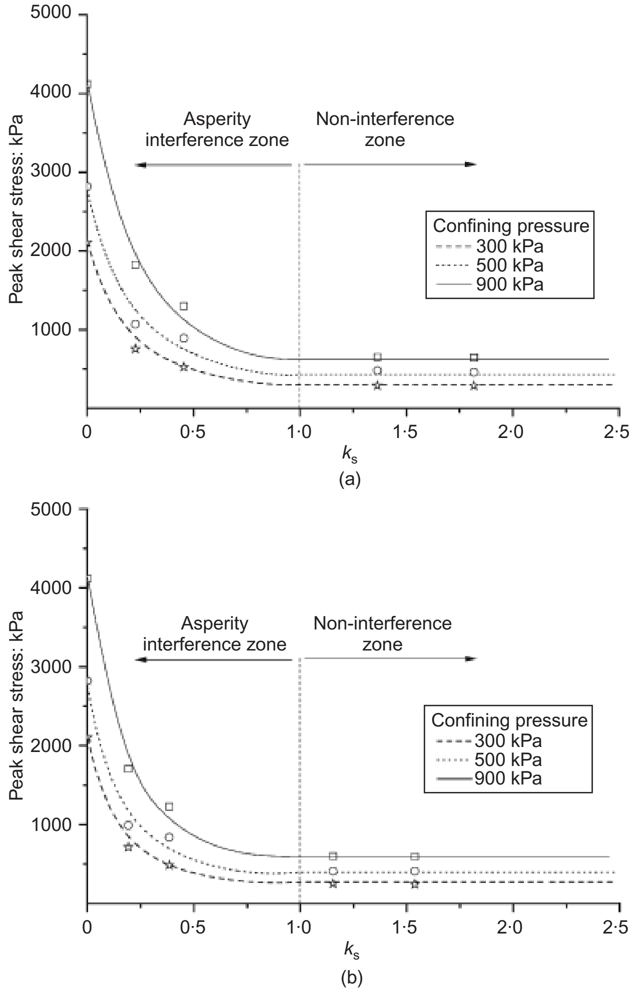

Fig. 5. Verification of shear strength model for infill saturations of (a) 50% and (b) 70%

Table 1. Empirical constants and critical *t/a* ratios for different infill saturations for replicated natural joints

Degree of saturation	35%	50%	60%	70%	85%
$(t/a)_{cr}$	1·0	1·1	1·2	1·3	1·4
α	1·3	1·5	1·7	2·0	2·2
β	3·0	2·6	2·3	1·8	1·5

CONCLUSIONS

This technical note has presented the first conceptual model for infilled joints that captures the role of the degree of infill saturation on the shear strength. In this model, two main zones were identified based on the normalised infill thickness ratio (k_s); when $k_s < 1$, the stress–strain behaviour is influenced by asperity interference, and the peak shear strength is mainly governed by rock-to-rock contact. Joint dilation was mainly observed in this region following initial joint compression. When $k_s > 1$, shearing only takes place through the infill marginalising the effect of rock–rock contact. Here, the shear strength is fully governed by the infill properties, whereby the propagation of the shear plane through the infill alone is accompanied by joint compression. The proposed conceptual model was successfully validated using triaxial data for imprinted natural joint profiles.

The proposed shear strength model has a number of limitations. First, as laboratory testing was focused on a narrow range of natural joint profiles, further testing of different irregular joints covering a much wider range of JRC is recommended. Moreover, further testing using different infill materials is required to build greater confidence in the proposed empirical model. Scale effects were not examined during this study. In spite of these limitations, the role of infill saturation on the joint shear strength could still be explained by the proposed conceptual model and the supporting laboratory data.

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NOTATION

A, B	components of proposed shear strength model
a	asperity height
c'	effective cohesion
k_s	ratio between $(t/a)_s$ and $(t/a)_{cr,s}$
S_r	degree of infill saturation
S_{res}	residual degree of saturation
s	matric suction
t	infill thickness
$(t/a)_{cr,s}$	critical (t/a) for degree of saturation $= s$
$(t/a)_s$	given (t/a) for a degree of saturation $= s$
u_a	pore air pressure
$(u_a - u_w)$	matric suction
u_w	pore water pressure
α, n, m	empirical constants defining soil water characteristic curve
α, β	empirical coefficients defining shape of functions A and B respectively
Θ	dimensionless water content
σ_n	normal stress
τ	peak shear strength of the joint
ϕ'	angle of effective internal friction of infill
ϕ_b	basic friction angle of the joint

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